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A study of radio frequency spectrum emitted by high energy air showers with LOFAR

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Abstract. The high number density of radio antennas at the LOFAR core in Northern Netherlands allows to detect radio signals emitted by cosmic ray induced air showers, and to characterize the geometry of the observed cascade in a detailed way. We present here a study of the radio frequency spectrum in the 30 − 80 MHz regime, and its correlation with some geometrical parameters of the extensive air shower. An important goal of this study is to find a correlation between the frequency spectrum and the primary particle type. Preliminary results on how the frequency spectrum changes as function of distance to the shower axis, and as function of primary particles mass composition are shown. The final aim of this study is to find a method to infer information of primary cosmic rays in an independent way from the well-established fluorescence and surface detector techniques, in view of affirming the radio detection technique as reliable method for the study of high energy cosmic rays.

1 Introduction

The LOw Frequency ARay (LOFAR) is a radio antenna array consisting of 50 stations spread in Northern Europe with a more dense core in Northern Netherlands [1]. Measurements of cosmic rays are performed mostly by using signals from the Low Band Antennas (LBAs) which operate in the frequency range 10 − 90 MHz. The LOFAR central array is instrumented with 20 scintillator detectors, the so-called LORA array [2], which provides triggers for cosmic ray data acquisition, and allows to reconstruct the arrival direction and the energy of primary particles. The LOFAR array detects cosmic rays in the energy range $10^{16} - 10^{18}$ eV.

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Analytical calculations [4, 5] and simulation studies [6] conducted at the beginning of years 2000 already showed a dependence of the radio frequency spectrum on cosmic ray air shower characteristics. Previous measurements of the frequency spectrum performed by LOPES did not show any significant dependence of the frequency spectrum with respect to the distance to the shower axis and to the arrival direction [7]. A recent analysis conducted at the Auger Engineering Radio Array (AERA) of the Pierre Auger Observatory, shows a dependence of the frequency spectrum to the properties of the primary particle [8]. This demonstrates that it is feasible to extrapolate information from the frequency spectrum with the current radio antenna arrays.

The goal of the anaysis described here is to find a reliable method for deriving information of the primary cosmic rays detected at LOFAR by performing a frequency spectrum analysis. Among radio experiments, LOFAR is the one with the most dense number of antennas, thus the most suitable for this kind of analysis. In order to find the best parameters which describe the correlation between primary cosmic ray information and the emitted radio signal, two methods have been applied, and a cross-check between real data and simulations has been done. Regarding real data, cosmic ray radio signals detected by LOFAR since 2011 have been analysed. For the simulation of radio signals, the CoREAS code [9], a plug-in of the CORSIKA particle simulation code, has been used.

2 Analysis and Results

In order to study a correlation between the radio frequency spectrum and the cosmic ray air shower characteristics, two methods have been applied to both simulations and real data: the percentile statistical method and the linear fit method. For each cosmic ray event detected by LOFAR, a set of CORSIKA simulations has been produced by using, as initial input, protons as primary particle, and energy and arrival direction as reconstructed from the real event. In the simulation set the antenna layout has been chosen in order to have a symmetric star-shape around the shower axis, in the plane perpendicular to the shower axis (hereafter, *shower plane*). The total number of antennas is 160, and they are distributed on 8 arms at an angle distance $\alpha = 45°$ between each other in the shower plane. Each antenna is 25 m distant from the previous one, thus covering an area of 500 m radius around the shower axis. Furthermore, the signal intensity in the time-domain is converted to the frequency-domain by applying a Fast Fourier Transform (FFT). The FFT distribution, as function of frequency, has been characterised by using the two following methods:

- **the percentile statistical method** → the FFT distribution has been integrated in the frequency range $30 - 70$ MHz, and the statistical percentile indicates the frequency value at which the integrated FFT distribution reaches a certain fraction of the total integral; a preliminary study on simulations has shown that the 50^{th} percentile, also known as *median*, i.e. the frequency value at which the integrated FFT distribution reaches half of the total integral, describes better the slope changing of the FFT distribution as function of distance to the shower axis [10];
- **the linear fit method** → the FFT distribution, in the logarithmic scale, has been fitted with a linear function in the frequency range $30 - 70$ MHz; the slope parameter of the fitted function has then been studied as function of distance to the shower axis.

These two analysis methods have been applied to all data detected by LOFAR since 2011 and to the corresponding simulated events. Figure 1 shows the distribution of the 50^{th} percentile frequency as a function of distance to the shower axis in the shower plane for both one simulated event and the corrisponding real event. The detected event has a primary energy of $(1.7 \pm 0.8) \cdot 10^{17}$ eV as reconstructed by the LORA scintillator array, and a value of the atmospheric depth where the cascade reaches its maximum development $X_{max} = (763 \pm 38)$ g/cm^2 as reconstructed by the Lateral Distribution Function method [11]. This real event has been compared with simulations, in particular with

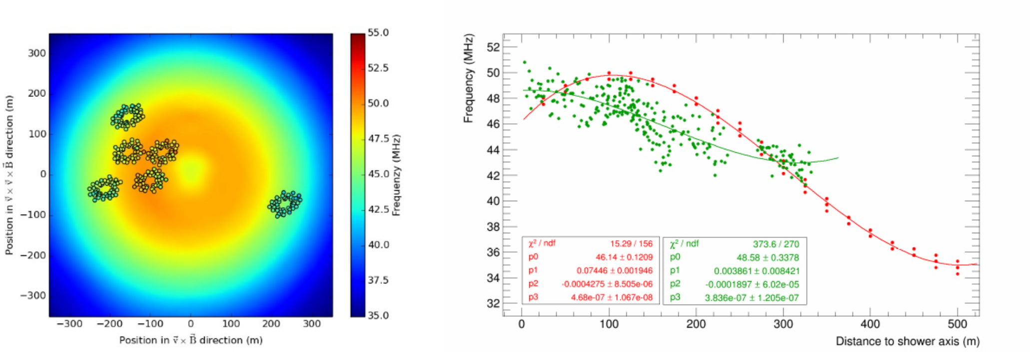

Figure 1. *Left*: comparison between the frequency distribution of the 50th percentile for one simulated event (background) and one real event detected by LOFAR LBAs (circles); the comparison is projected onto the shower plane, and the colour scale refers to the frequency of the 50th percentile. *Right*: distribution of the 50th percentile frequency as function of distance to shower axis in the shower plane for one simulated event (red points) and the corresponding real event (green points); the two distributions have been fitted with a third polynomial function (solid line).

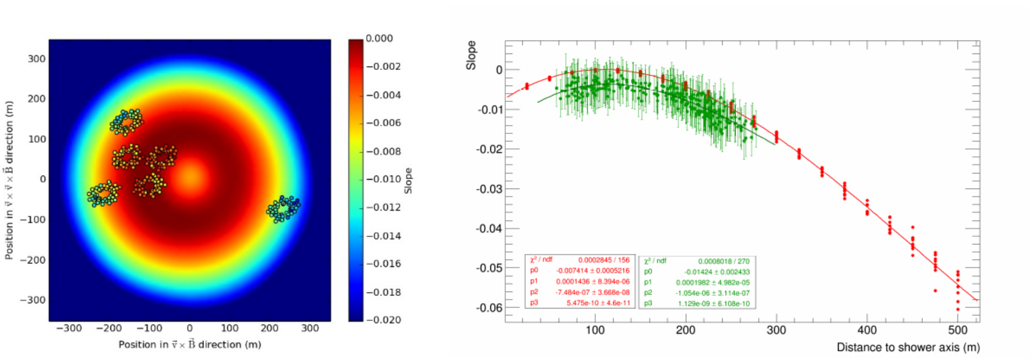

Figure 2. *Left*: comparison between the distribution of the linear fit slope for one simulated event (background) and one real event detected by LOFAR LBAs (circles); the comparison is projected onto the shower plane, and the colour scale refers to the slope of the linear fit. *Right*: distribution of the linear fit slope as function of distance to shower axis in the shower plane for one simulated event (red points) and the corresponding real event (green points); the two distributions have been fitted with a third degree polynomial function (solid line).

the one having the value of X_{max} closest to the real one, i.e. X_{max} = (764 ± 17) g/cm^2, as evaluated from the method described in [12]. Figure 2 shows the distribution of the slope parameter, as obtained from the linear fit method, as function of distance to the shower axis in the shower plane, for both one simulated event and the corrisponding real event. The cosmic ray event and the simulated one are the same event as shown in figure 1 . For both methods, simulations and real data have been fitted with the following third degree polynomial function $p_0 + p_1 \cdot d + p_2 \cdot d^2 + p_3 \cdot d^3$, where d is the distance of each antenna to the shower axis in the shower plane.

A study about the dependence of the frequency spectrum with respect to X_{max} has been performed as well. Figure 3-*left* shows the distribution of the 50th percentile frequency as function of X_{max} for

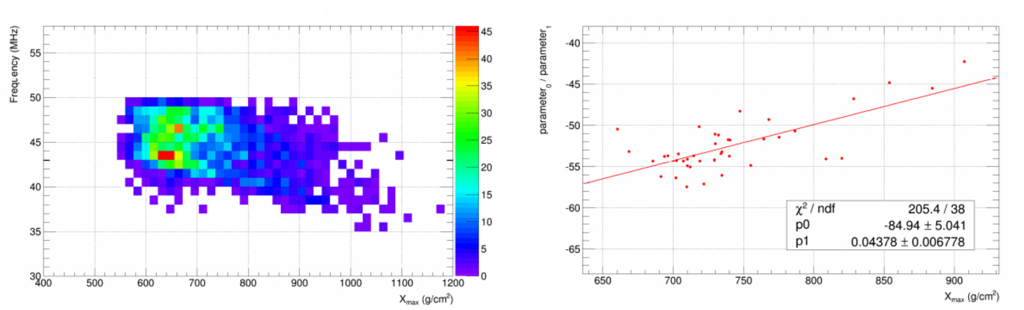

Figure 3. *Left*: distribution of the 50th percentile frequency as a function of X_{max} for simulated events in the energy range $10^{17} - 2 \cdot 10^{17}$ eV; the colour scale refers to the number of events. *Right*: distribution of p_0/p_1 as a function of X_{max}; p_0 and p_1 are the parameters obtained by fitting the slope of the FFT as function of distance to shower axis with a third degree polynomial function.

simulated events in the energy range $10^{17} - 2 \cdot 10^{17}$ eV. Figure 3-*right* shows the distribution of p_0/p_1 as function of X_{max} , where p_0 and p_1 are the parameters obtained by fitting the slope of the FFT as function of distance to shower axis with the third degree polynomial function for different simulated events. Both plots of figure 3 depict a dependence of the frequency spectrum with respect to X_{max} .

3 Conclusions and Outlook

A study of the radio frequency spectrum in the 30 – 70 MHz regime has been performed. Preliminary results depict a very strong correlation between the feature of the frequency spectrum and the distance to the shower axis. This is highlighted by a good agreement between simulations and real event for both analysis methods, as shown in figures 1 and 2 . A correlation between the frequency spectrum and the atmospheric depth of the shower maximum X_{max} has been studied as well. Results performed on simulated data show a clear correlation (figure 3), while this dependence on real data is still under investigation.

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